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Modeling methodology for assessing crop production potentials in Canada

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CONTENTS

	Page
Abstract	iii
Introduction	1
Climatic Data	1
Station Data	2
Grid Square Data	2
Soil Unit Data	2
Definition and Calculation of the Growing Period	3
Procedure for Estimating Crop Potential Net Biomass and Dry Matter Yield Production	4
Calculation of Respiration Losses (C_T)	6
Calculation of Gross Biomass Production (b_{GM})	6
Correction for Temperature	8
Correction for Crop Development	10
Calculation of Potential Dry Matter Yield	10
Procedure for Determining Anticipated Net Biomass and Dry Matter Yields	12
Calculation of Moisture Stress Losses	14
Yield Response Factor (K_y)	14
Evaluation of ET_A/PE	14
Evaluation of LAI	19
Evaluation of the Workability Parameter	20
A Sample Calculation	24
Acknowledgements	27
References	28

Abstract

The methodology by which the rainfed crop production potentials for various crops can be determined from generalized photosynthetic responses to average climatic factors of radiation, temperature and precipitation in Canada is presented. This bulletin provides details and assumptions on the crop growth model used to estimate the potential net biomass and dry matter yields. It also provides details on the assumptions made in development of the yield reducing agroclimatic constraint indices involving moisture stress and workability. These indices are applied against the potential values to estimate the agroclimatically attainable or expected net biomass and dry matter yields. The described methodology is not intended for predicting real time crop production values. Instead, it is designed as a land evaluation tool for assessing the long-term land resource capability for crop production on a continental basis.

Résumé

Dans le présent bulletin, on expose les méthodes qui permettent de déterminer les possibilités de production de diverses cultures en régime pluvial en fonction de leurs réactions photosynthétiques générales aux facteurs climatiques, notamment au rayonnement, à la température et aux précipitations. On y donne, en outre, des précisions sur un modèle de croissance des cultures et sur les hypothèses relatives à ce modèle qui sert à évaluer les rendements potentiels nets en biomasse et en matière sèche. Enfin, y figurent aussi des précisions sur les hypothèses concernant l'établissement des indices relatifs aux facteurs agroclimatiques qui réduisent le rendement, y compris le stress hydrique et les possibilités de travail. Ces indices sont appliqués aux valeurs potentielles afin d'évaluer les rendements nets en biomasse et en matière sèche qu'il est possible d'atteindre ou qui sont prévus en tenant compte des facteurs agroclimatiques. Les méthodes susmentionnées n'ont pas été mises au point pour la prévision ponctuelle des rendements des cultures; elles ont plutôt été conçues comme outil d'évaluation des terres devant servir à estimer, à long terme et à l'échelle du continent, le potentiel des terres en production végétale.

Introduction

F.A.O. projections estimate that to support the predicted world population in the year 2000 would require an increase in agricultural production of 60 percent. It is uncertain whether there are sufficient global land resources to accomplish this increase. At present, there is insufficient precise data upon which to base a reliable answer.

F.A.O. began a study, in 1976 involving global potential land use by agroecological zones. The aim of the project was to obtain a first approximation of the production potential of the world's land resources, and to provide the physical data base necessary for planning future agricultural development.

Initially, the study dealt with rainfed production potential for eleven crops in developing countries. At the same time F.A.O. requested the cooperation of a number of developed countries, including Canada, in utilizing their methodology to evaluate production potential of various crops. This would serve as a test of the overall concept and would serve to expand the global data base. A project involving the assessment of the production potential of five crops, wheat, maize, soybean, potato and phaseolus bean, was begun in Canada in 1978 in response to this request.

In brief, the F.A.O. (1978) procedures involved in assessing the rainfed crop production potential include the following:

1) Inventorying the existing land resources for each region including the climatic resources and the soil resources;
2) Matching the various climatic and soil requirements for each crop with existing land resources and calculating constraint free potential yields for each crop;
3) Evaluating the anticipated yield potential by determining the yield reducing factors of a) moisture stress; b) losses due to diseases, pests and weeds; c) loss due to climatic variability affecting yield components and quality; and d) workability.
4) Assessing the soil suitability of individual areas for the production of each crop.
5) Comparing the agroclimatic suitability with the soil suitability assessment in evaluating the overall land suitability for the production of each crop.

This paper documents the methodology used in evaluating the constraint free potential yield and the yield reducing constraints required in estimating the agronomically attainable or anticipated yields for wheat, maize, soybean, potato and phaseolus bean crops in Canada. Results of the inventorying procedures (point 1) and the modelling application (points 4 and 5) for Canada, however, are not presented here, but are presented elsewhere (Dumanski and Stewart, 1981).

Climatic Data

The procedures for estimating the potential and anticipated net biomass and dry matter yields described in the following sections are designed to evaluate the long-term crop production capability on a continental basis using basic climatic information. Basic data in this

instance refers to long-term monthly averages of climatic elements such as temperature, precipitation, incoming solar radiation, windspeed and vapour pressure. These data are readily obtained from observation networks or can be derived using simple empirical expressions.

The basic climatic data source used in the calculation of potential and anticipated yields was the 1941-70 Canada Normals (Atmospheric Environment Service - Environment Canada). Monthly normals provided by the AES were obtained in the form of actual station data and a 1290 equal area grid system.

Maximum and minimum air temperature and precipitation data were available from 1068 stations located throughout the country. Values for vapour pressure, windspeed and incoming global solar radiation were assigned to each station by superimposing the station locations onto a 1290 equal area grid square network covering the land mass of Canada.

Grid square climatic information was obtained from the Atmospheric Environment Service - Environment Canada in the form of a 1290 equal area grid square network. For each grid square, climatic data including precipitation, mean, maximum and minimum air temperature (reduced to sea level), vapour pressures, windspeed and incoming global solar radiation, represented an area 100 km by 100 km. These data were derived by computer interpolation of climatic normals from over 1800 full and part-time climatological stations located throughout Canada (G. den Hartog, personal communication).

In this study soil information is integrated with the climatic and crop phenological information as a part of the overall assessment procedure. Since neither the station nor grid square locations could be used to adequately express the geographical distribution of soils the soil as a unit is used instead. More specifically, the Soils Map of Canada (Clayton et al., 1977) is used in this study as the basis for illustrating all computations geographically. Individual soil units defined by Clayton et al. are essentially those presented in the 1:5 million Soils Map of the World (FAO, 1974) except that the Soils Map of Canada is a refined version of the Canadian portion giving more detailed subdivisions of the larger soil map units presented on the Soils of the World map.

The soils Map of Canada consists of 755 specific soil units. Physical characteristics of each as well as the geographical extent are discussed in detail by Clayton et al. (1977). Climatic data for each of the 755 soil map units contained in the Soils Map of Canada were largely derived from the above grid square data. This was accomplished by superimposing the grid square framework onto the 1:5 million scale Soils of Canada Map and estimating the area of each soil unit contained in each grid square. From this the basic climatic data for each soil unit was obtained from a simple weighting procedure in the form:

$$D_K = \sum_{i=1}^{n} (A_{Ki} \cdot V_i)/A_{KT}), \tag{1}$$

where: D is the weighted arithmetic mean for soil unit K;
i is a subscript denoting a grid square containing soil unit K;
(i-n) represents the number of grid squares containing soil unit K;
V is the climatic variable for grid square i;
A_{Ki} is the area of soil unit K contained in grid square i;
A_{KT} is the total area of soil unit K.

Using eq. (1) the entire grid square climatic inventory was converted to values representing individual soil map units.

In certain instances the grid square data were considered inadequate for expressing the climatic information of various soil units particularly the mountainous area of British Columbia. To correct this situation station data was used to compute the climatic information for each soil unit by averaging the data for all stations contained in each soil unit. This was quite reasonable since the main intermountain agricultural areas contained one or more stations. For soil units containing no stations, however, the grid square data were used.

Definition and Calculation of the Growing Period

In order to estimate the potential for crop production the time period available for crop growth or growing period first has to be determined. The FAO study (1978) defined the growing period as the length of time during the year when precipitation exceeds half the potential evapotranspiration plus the period required to evaporate or reduce the water stored in the soil profile by 100 mm. Temperature is considered by reducing the number of days from the above moisture growing period over which the mean air temperature is less than 6.5°C.

This is a moisture based definition and applies in areas where moisture rather than heat is the dominant yield controlling factor. In Canada, however, temperature is the major limiting factor to crop growth - not water. As a result, the growing period is defined from a thermal point of view based on the "frost free period". Specifically the growing season is defined as the period in days during the year when the mean minimum air temperature is greater than or equal to 5°C. Use of the 5°C isotherm for the start and end of the growing period represents with a 50 percent probability the average date, calculated from 30-year climatic normals data, for the last spring and first fall frosts (0°C) (Sly and Coligado, 1974). Moisture is not considered in the growing season definition since the effects of moisture shortages on crop development and yields is evaluated directly in the quantification of the moisture stress agroclimatic constraint.

The Julian dates for the growing season start and end were derived from the monthly minimum air tempreature normals data as follows: first, the monthly values were converted to daily values using the Brooks (1943) sine-curve interpolation technique. The Start and End of the growing season was then derived by computer interpolation of the dates the minimum air temperature first exceeded in the spring, and fell below in the fall, $5^{o}C$. From these dates the growing season length was computed as START-END+1.

Daily values of maximum temperature, vapour pressure, incoming global solar radiation, windspeed and precipitation were generated from the monthly normals using the Brooks (1943) interpolation technique. Mean growing season values were then computed for each variable by summing the daily values from the start of the growing season to the end and dividing by the growing season length. In all cases since normals data are used, representing the 30-year period from 1941-71, it is assumed that the data is normally distributed throughout the month on both a weekly and daily basis.

Procedure for Estimating Crop Potential Net Biomass and Dry Matter Yield Production

The potential or maximum constraint free yield attainable by a crop is primarily determined by its genetic characteristics and how well it is adapted to the existing environment. Constraint free yield is defined as the harvested dry matter yield of a high producing variety, that can be produced under conditions where water, nutrients and weeds, pests and diseases do not limit crop growth. Under these conditions the crop yield is limited only by the crop physiological responses to the amount of radiant energy received by the crop, the temperature over the course of the growing period and the length of the growing period.

Procedures developed by F.A.O. (1978) are used to compute constraint free net biomass production. Assuming no moisture, nutrient, weeds, pests and disease limitations to crop growth, the constraint free or potential net biomass production is computed as:

$$B_N = 0.36\ b_{GM}/(1/N + 0.25C_T), \qquad (2)$$

where: b_{GM} is the crop seasonal rate of maximum gross biomass production,
C_T is a temperature function defining the crop maintenance respiration loss developed by McCree (1974), and
N is the growing season length.

In the derivation of eq. (2) it assumed that: a) the cumulative potential growth rate of any crop over the course of the growing season is S-shaped as shown in Figure 1a; b) the change in growth rate over the course of the growing season is in the form of a normal distribution with the maximum rate occurring at the mid point in the crops life cycle (Fig. 1b); and c) from (a) and (b) the seasonal average rate of gross biomass production is 50% of the seasonal maximum gross biomass production. As seen in eq. (2) if values of b_{GM} and C_T can be estimated the crop potential net biomass production can be derived by inserting the appropriate growing season length. The following sections outline the procedures used to evalute C_T and b_{GM} in this study.

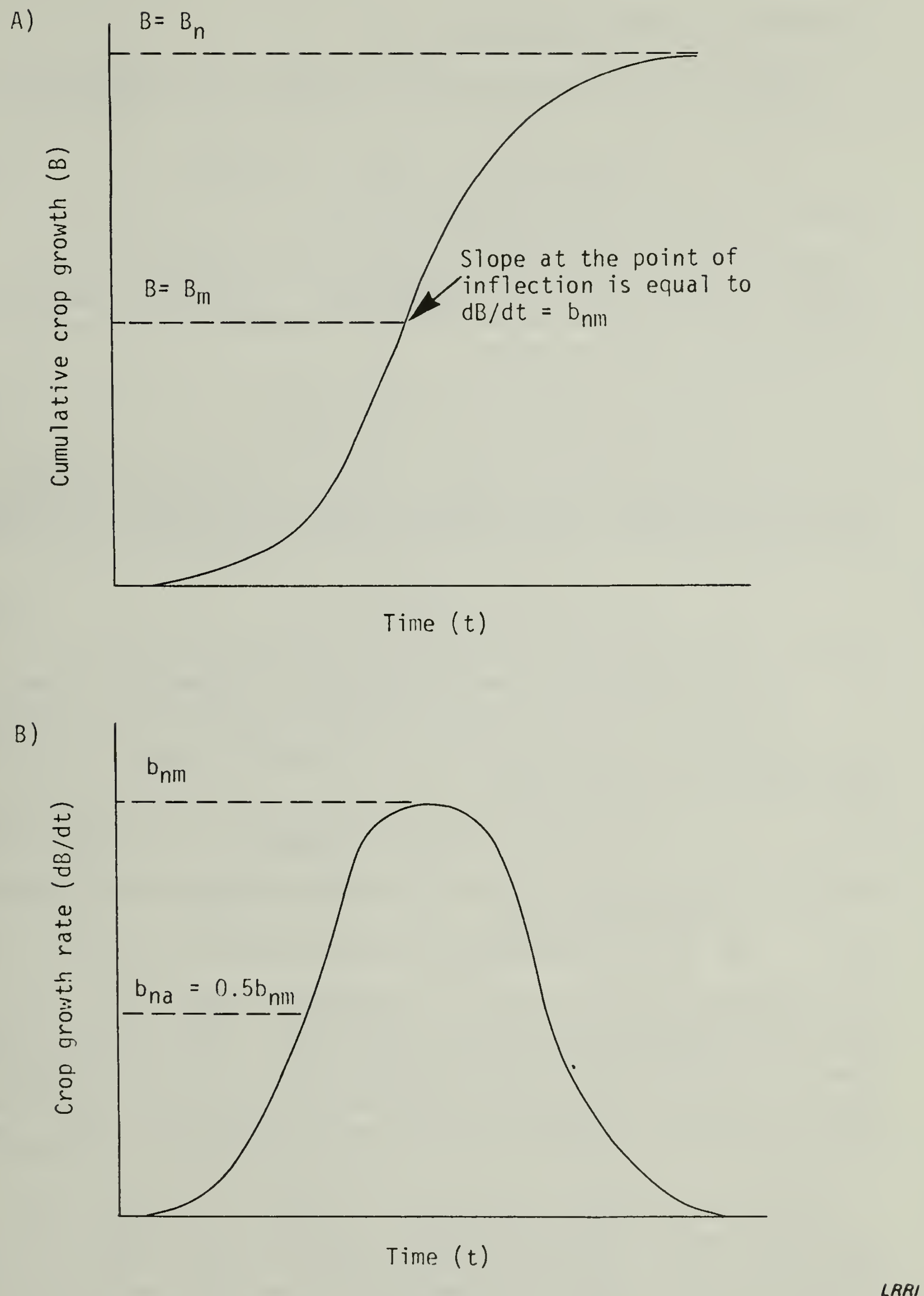

Fig. 1A Typical cumulative crop growth curve showing the point of inflection during the period of maximum growth when the slope dB/dt is equivalent to the maximum rate of net biomass production (b_{nm}).

Fig. 1B The normal shape of the curve of crop growth rate plotted against time showing average crop growth rate (b_{na}) = $0.5b_{nm}$

Calculation of Respiration Losses (C_T)

Values of C_T were obtained using the expression developed by McCree (1974):

$$C_T = C_{30} \; (0.044 + 0.0019T + 0.0010T^2), \qquad (3)$$

where: T is the mean air temperature, and
C_{30} is the maintenance respiration coefficient at 30°C.
At 30°C, McCree (1974) observed values for C_{30} of 0.0283 and 0.0108 for a legume and non-legume crop, respectively. The former is used in the determination of B_N for soybean and phaseolus bean, while the latter is used for corn, wheat and potato.

Calculation of Gross Biomass Production (b_{GM})

The method developed by deWit (1965) is used to evaluate b_{GM}. Using this approach, a crops maximum rate of gross biomass production, described by a characteristic set of standard variables at an assumed leaf area index of 5.0, can be determined for any location as:

$$b_{GM} = F \times b_o + (1-F) \times b_c, \qquad (4)$$

where: F is the fraction of the day that the sky is overcast,
b_o is the rate of biomass production on overcast days, and
b_c is the rate of biomass production on perfectly clear days.

The fraction of the daytime when the sky is overcast, (F), is evaluated from the expression:

$$F = (PAR_c - 0.5k{\downarrow}) \; / \; 0.8 \; PAR_c, \qquad (5)$$

where: PAR_c is the photosynthetically active radiation on perfectly clear days, and
$k{\downarrow}$ is the incoming global shortwave solar radiation.

Estimates of PAR_c, b_o and b_c determined by deWit (1965) for a crop, with a maximum rate of CO_2 exchange (P_m) of 20 kg ha^{-1} hr^{-1}, were used in the calculation of b_{GM} in equation (4). Data representing the mean monthly values over the latitudinal extent of Canada are given in Table 1. In his calculations, deWit assumed that the photosynthetically active radiation on totally overcast days is 20 percent of PAR_c, and that PAR_c is 50 percent of $k{\downarrow}$ in both clear and overcast conditions.

Values of b_o and b_c, illustrated in Table 1, as mentioned above represent computed values for deWit's standard crop. Under actual field conditions, these photosynthetic rates in many instances can be exceeded or not reached at all depending on how well the actual crop growth compares to deWit's standard crop. Therefore, b_{GM} values obtained from eq. (4) must be corrected for the various factors causing divergence of the standard crop from actual crop performance. In the FAO methodology two factors involving temperature and crop development are used to correct deWit's standard crop estimates. These are outlined in the following sections.

TABLE 1. Photosynthetically Active Radiation on Very Clear Days (PAR_c) and the Daily Gross Photosynthesis rates of Crop Canopies on Very Clear (b_c) and Overcast (b_o) Days for a Standard Crop P_m - 20kg CH_2O HA^{-1}

North Lat.		Jan. 15	Feb. 15	Mar. 15	Apr. 15	May 15	June 15	July 15	Aug. 15	Sept. 15	Oct. 15	Nov. 15	Dec. 15
40^o	PAR_c	131	190	260	339	396	422	413	369	298	220	151	118
	b_c	218	283	353	427	480	506	496	455	390	314	241	204
	b_o	99	137	178	223	253	268	263	239	200	155	112	91
50^o	PAR_c	73	131	207	304	380	418	405	344	254	163	92	61
	b_c	147	223	310	409	484	522	509	448	358	260	173	130
	b_o	60	100	150	207	251	273	265	230	178	121	73	51
60^o	PAR_c	22	72	149	260	356	408	389	309	201	103	37	14
	b_c	66	151	254	383	487	544	523	436	316	195	94	49
	b_o	19	60	114	187	245	276	265	216	148	82	31	11
70^o	PAR_c	0	20	89	209	331	408	380	269	142	45	2	0
	b_c	0	65	185	350	506	612	575	427	262	114	7	0
	b_o	0	16	74	158	241	291	273	200	112	38	1	0

deWit (1965) Table 6 b_c, b_o in kg/ha/day

P_m = maximum crop growth rate

Correction for Temperature

The maximum rate of CO_2 exchange (P_{max}) and, therefore, the gross biomass production is dependent on both the photosynthetic pathway of the species and the temperature at which the crop photosynthesizes. Since the deWit's standard crop assumes P_m = 20 kg $ha^{-1}hr^{-1}$, crops maintaining maximum production rates differing from this have to be corrected either up or down depending on the comparison of the crops actual P_m to deWit's value. Correction criterion used in this study are as follows: if $P_m \geq 20$kg $ha^{-1}hr^{-1}$, b_{GM} is increased by:

$$Y/5/100 \times f \times b_o + Y/2/100 \times (1-F) \times b_c, \tag{6a}$$

van Ittersum (1972), F.A.O. (1978); while if $P_m \leq 20$ kg $ha^{-1}hr^{-1}$, b_{GM} is decreased by:

$$Y/2/100 \times F \times b_o + Y/100 \times (1-F) \times b_c. \tag{6b}$$

In the above equations the parameter Y, representing the percentage by which the crop maximum photosynthetic rate (P_m) exceeds or falls below the standard crop value of 20 kg/ha/hr, is estimated as:

$$Y = ((P_{ma} - 20))/20) \times 100, \tag{7}$$

and P_{ma} is the actual crop maximum photosynthetic rate.

Values of P_{ma} in this study were derived from relationships developed by F.A.O. (1978). Curves illustrating the relationships of P_{ma} with temperature for the two main crop groups, containing the 5 crops considered in this study, are illustrated in Fig. 2 as taken from F.A.O. (1978), Fig. 3.1. Polynomial expressions were fit to each of the curves depicted in Fig. 2 facilitating computer calculation of the maximum photosynthetic rate for each group. The derived expressions were as follows:

$$\text{GROUP I } P_{ma_1} = -11.308 + 3.524\ T_{MDT} - 0.097\ T_{MDT}^2, \tag{8a}$$

and

$$\text{GROUP IV } P_{ma_4} = -433.67 + 48.67\ T_{MDT} - 1.576\ T_{MDT}^2 + 0.017\ T_{MDT}^3, \tag{8b}$$

where: T_{MDT} is the mean daytime temperature calculated from the mean (T_{mean}), maximum (T_{max}), and minimum (T_{min}) temperature data in the form:

$$T_{MDT} = T_{mean} + (2(T_{max} - T_{mean})/3.1416). \tag{9}$$

P_m values for wheat, soybean, potato and phaseolus bean crops were obtained using eq. (8a) while values for corn were computed using eq. (8b).

FIG.2

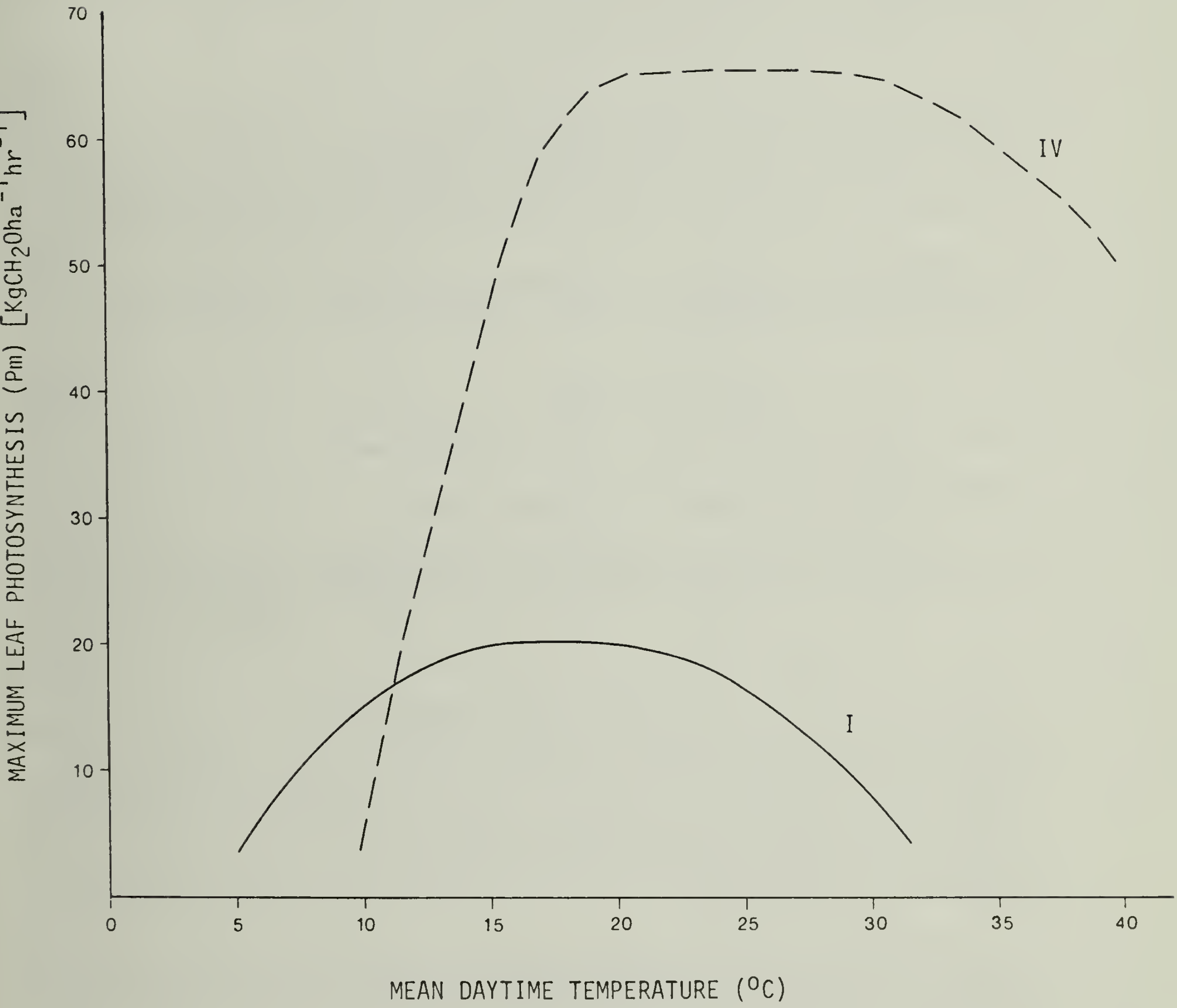

Fig. 2 Average relationship between maximum leaf photosynthesis rate and temperature for crop groups I and IV. (from Fig. 3.1, F.A.O., 1978)

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Correction for Crop Development

For a given value of P_{ma} the magnitude of b_{GM} depends on the Leaf Area Index (LAI), which is an expression of crop development, representing the fraction of the soil surface covered by the crop. Since deWit's standard crop assumes that LAI = 5.0 in the calculation of P_m, if the actual crop LAI is less than 5.0, then b_{GM} has to be corrected for this difference. F.A.O. (1978) has derived a relationship relating the maximum crop growth rate (MCGR) to LAI. A polynomial expression fit to the relationship illustrated in F.A.O. (1978), Fig. 7.3 in the form:

$$MCGR = 0.004 + 0.316\ LAI - 0.032\ LAI^2, \tag{10}$$

is used to correct the maximum crop growth rate in the event the actual crop LAI<5.0. When the LAI>5.0, MCGR is set equal to one. In this situation it is assumed that the effect of LAI on b_{GM} is negligible since the coincidence of complete ground cover and light interception is achieved by the crop canopy at this point in time.

With the inclusion of the correction for crop development the "actual" crop potential net biomass production (B_{NACT}) for a crop of N days can be determined as:

$$B_{NACT} = B_N \times MCGR, \tag{11}$$

where: B_N is obtained from eq. (2) and MCGR from eq. (10), respectively.

Calculation of the Potential Dry Matter Yield

The potential net dry matter yield is obtained from the net biomass production values by taking into account the appropriate harvest index (H_I):

$$B_y = B_{N_{ACT}} \times H_I. \tag{12}$$

H_I the harvest index, is defined as the fraction of the crop net biomass production that is economically useful. Harvest index values for each of the crops listed in Table 2 were obtained from F.A.O. (1978). These figures represent the range of values to be expected over various ranges in the growing season length. From these data H_I values representing the exact growing season length were derived by linear extrapolation between the minimum and maximum values recorded for each growing season length range.

It should be remembered that factors such as the genetic potential of the crop cultivar, moisture conditions and farming practices can cause the value of H_I to fluctuate considerably from yar to year. For this reason values listed in Table 2 are assumed representative of the long-term averages corresponsing to those that would occur with little or no agronomic constraints (F.A.O., 1978).

TABLE 2. Crop Characteristics Considered in the Potential Net Biomass and Yield Calculations

Crop		Growing Season Length (Days) 75-89	90-119	120-149	150-179	180
Spring Wheat	GSL*	110	110	110	110	110
	LAI	3.1-3.7	3.7-5.0	3.7-5.0	3.7-5.0	3.7-5.0
	HI	0.11-0.28	0.29-0.40	0.40	0.40	0.40
	DMMP	.85	.85	.85	.85	.85
Maize	GSL*	130	130	130	130	130
	LAI	2.5-3.0	3.0-4.0	3.7-4.0	3.7-4.0	3.7-4.0
	HI	0.22-0.15	0.15-0.35	.35	.35	.35
	DMMP	.85	.83	.83	.83	.83
Soybean	GSL*	130	130	130	130	130
	LAI	2.5-3.0	3.0-4.0	3.0-4.0	3.0-4.0	3.0-4.0
	HI	0.2-0.29	.30	.30	.30	.30
	DMMP	.85	.85	.85	.85	.85
Potatoes	GSL*	140	140	140	140	140
	LAI	2.5-3.0	3.0-4.0	3.0-5.0	3.0-5.0	3.0-5.0
	HI	0.45-0.59	.60	.60	.60	.60
	DMMP	.32	.32	.32	.32	.32
Phaseolus Bean	GSL*	120	120	120	120	120
	LAI	2.5-3.0	3.0-4.0	4.0	4.0	4.0
	HI	0.19-0.29	0.3	0.3	0.3	0.3
	DMMP	.85	.85	.85	.85	.85

LAI & HI - From F.A.O. (1978) Tables 7.4 and 7.6

*GSL is the maximum growing season length required to mature the crop under average Canadian conditions.

LAI is the average Leaf area index during the growing period

HI is the average harvest index

DMMP is the percent dry matter in the main product.

Procedure for Determining Anticipated Net Biomass and Dry Matter Yields

Net biomass and yield as outlined above provide estimates of the potential which can be expressed under conditions that are free from yield reducing factors (constraints) within the growing period. In deriving actual anticipated yield values, however, yield losses due to various agroclimatic constraints must be considered. According to the FAO (1978) methodology yield losses in rainfed crop production are governed by agroclimatic constraints involving: moisture stress; pests, diseases and weeds; water stress, pests and diseases, and climatic effects on yield components, yield formation and quality of produce; and workability constraints. These constraints, as pointed out by F.A.O. (1978) are complex and dynamic and their interrelations are extremely difficult to assess quantitatively. For this reason values were arbitrarily selected to represent the constraints in the various Agro-Ecological Zones of Africa. Selection of the constraint values was based on a bulk figure reduction. For example, if the particular constraint was negligible a value of 0 was assigned; if the constraint was moderate a 25 percent value was assigned while a value of 50 percent was given if the constraint was considered severe. Values representing the various constraints were assigned to each region considering their effects on both high and low input farming practices.

This study deviates from the F.A.O. methodology in that two of the constraints are assessed quantitatively. These include yield losses due to moisture stress and those due to workability. Losses in Canada due to the effects of diseases, pests and weeds are assumed negligible as a result of high input farming practices, which for the most part have kept yield losses to less than 15 percent (W. Saidak, personal communication). Similarly yield losses due to climatic constraints on yield components, yield formation and quality of produce were ignored since it is believed that losses associated with this constraint are in part taken into account in the quantification of losses due to moisture stress and workability. Following this the actual or anticipated net biomass (B_{ANT}) production for each crop was calculated as

$$B_{ANT} = B_{N_{ACT}} \times MSF \times WP, \qquad (13)$$

and the actual of net dry matter yield as:

$$B_{Y_{ANT}} = B_{ANT} \times H_I. \qquad (14)$$

MSF and WP are respectively the yield losses atrributed to moisture stress and workability. The following sections outline the techniques used in this study for estimating MSF and WP.

TABLE 3 - Yield Response Factor to Moisture for Canadian Crop Conditions

Crop	Yield Response Factor (K_y)
Wheat	1.15
Corn	1.25
Soybean	1.20*
Potato	1.10
Phaseolus Bean	1.15

From - Table 2. Doorembos and Kassam (1979).

* - Kassam (personal communication). The values expressed in Table 2 of Doorembos and Kassam (1979) represent cultivars grown in tropical and subtropical conditions. Temperate cultivars typically grown in Canada are much more sensitive to moisture stress.

Calculation of Moisture Stress Losses

An expression relating the relative yield decreases to the relative evapotranspiration deficit was used to quantify the effect of moisture stress on yield losses. The relationship is expressed in the form

$$(1 - \frac{Y_A}{Y_P}) = (1 - \frac{ET_A}{PE}) K_y \tag{15}$$

where: Y_A is the actual harvested yield,
Y_P is the potential or maximum harvested yield,
ET_A is the actual evapotranspiration,
PE is the potential or maximum evapotranspiration, and
K_y is an empirically derived yield response factor.

Rearranging equation (15) the actual crop yield Y_A can be computed as:

$$Y_A = Y_P (1-K_y (1- \frac{ET_A}{PE}) = Y_P \times MSF, \tag{16}$$

where: $$MSF = 1- K_y (1 - \frac{ET_A}{PE}) \tag{16a}$$

is the moisture stress factor (MSF). Therefore, if K_y, ET_A and PE are known or can be estimated, yield reductions due to moisture stress can be determined from equation (17). The following section discusses the procedures used to evaluate these parameters.

Yield Response Factor (K_y)

Values of the yield response factor (K_y) used in the solution of equation (17) for each crop are listed in Table 3 as taken from Doorembos and Kassam (1979). These values assume that the relationship between relative yield (Y_A/Y_P) and relative evapotranspiration (ET_A/PE) is linear and is applicable for moisture deficits up to 50 percent, i.e. ($1 - ET_A/PE = 0.5$). Where moisture deficits exceed this limit it is assumed that the linearity of these relationships remains constant.

Evaluation of ET_A/PE

The relative moisture deficit was evaluated using a soil moisture budgeting procedure expressed in the form

$$ET_A/PE = \frac{\sum_{i=GSS}^{GSE} (P_i + \Delta S - R_i)}{\sum_{i=GSS}^{GSE} PE_i} \tag{18}$$

where: GSS is the growing season start (Julian date),
GSE is the growing season end (Julian date),
P is the daily precipitation,
R is the daily runoff,
PE is the potential evapotranspiration, and
ΔS is the change in available moisture storage between the start of the growing season and day i.

The available soil moisture in storage during the growing season is monitored on a daily basis using the expression

$$S_i = S_{i-1} - PE_{S_i} \times (AE_s / PE_{S_i}) - PE_{P_i} \times (AE_p / PE_{P_i}) + P_i - R_i, \quad (19)$$

where: S_i is the available soil moisture at the end of the day,
S_{i-1} is the available soil moisture at the beginning of the day,
PE_s is the potential evaporation from bare soil surface,
PE_p is the potential transpiration by the crop canopy,
AE_s/PE_s is the ratio of actual to potential bare soil evaporation, and
AE_p/PE_s is the ratio of actual to potential plant transpiration.

In the solution of equation (18) and (19) the procedures developed by Ritchie (1972, 1974) describing the partitioning of evapotranspiration between base soil evaporation and plant transpiration for a developing row crop was used.

Potential evapotranspiration above the crop canopy (PE) is computed first, using the combination equation of Penman (1963) in the form:

$$PE = (S/\alpha)Q^* + 0.262\ (1+0.0061\ U)\ (e_s - e_a)\ \left(\frac{S}{\alpha}+1\right)^{-1} \quad (20)$$

where: S is the slope of the saturation vapour pressure curve at the mean air temperature (T_m),
α is the psychrometric constraint,
U is the windspeed at the 2m height,
e_s is the saturation vapour pressure at T_m, and
e_a is the mean vapour pressure of the air.

For the purpose of this study the soil heat flow is assumed negligible over the course of the growing season and is ignored in the calculation of PE.

Net radiation above the crop canopy (Q*) is estimated using the empirical relationship (Ritchie, 1974).

$$Q^* = (0.77K{\downarrow}+(0.00414(T_m-7.75)^{1.8}((1.35K{\downarrow}/K{\downarrow}_c)-0.35)-2.61))59. \quad (21)$$

where $K\downarrow$ is the incoming global solar radiation measured above the crop canopy (mm of water equivalent),

$K\downarrow_c$ is the incoming global radiation expected for perfectly clear skies (mm of water equivalent), computed as $K\downarrow_c = 9.4 - 3.34 \sin(0.986(J-80))$ where J is the Julian date and the argument of the same function is in degrees.

Potential base soil evaporation below the crop canopy (PE_s) was calculated as

$$PE_s = 0.8\left(\frac{S}{\alpha}\right)Q^*_s + 0.262\,(1+0.0061\,U_s)\,(e_o-e_a)\left(\frac{S}{\alpha}+1\right)^{-1}, \tag{22}$$

where: Q^*_s is the net radiation below the crop canopy determined as $Q^*_s = Q^*_{AC}\exp(-0.4\,LAI)$, and

U_s is the windspeed corrected from the 2m height to the surface where $U_s = U^*\,(0.4\,LAI)$.

Ritchie (1974) used an empirical expression to distinguish potential bare soil evaporation from potential plant transpiration in the form

$$PE_p = PE \times (-0.21 + 0.70\,LAI^{\frac{1}{2}}). \tag{23}$$

Equation (23) is valid for leaf area indexes (LAI) in the range 0.1 to 2.7. When LAI is greater than 2.7 Ritchie found that PE_p was independent of LAI and equation (23) reduces the $PE_p = PE$.

Actual evaporation (AE_s) and transpiration (AE_p) values from the soil surface and plant canopy were obtained using an extrapolation technique wherein the ratio of actual to potential evaporation is related to the available soil moisture in storage as shown in Fig. 3.

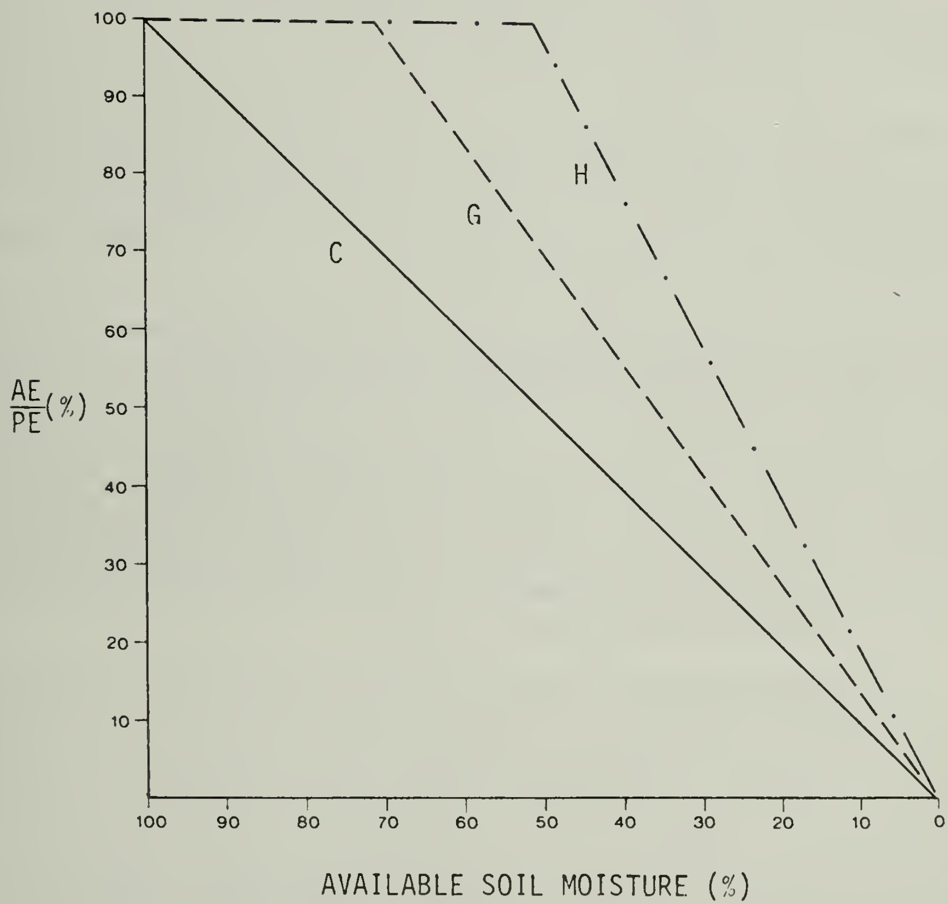
In the budgeting procedure described by equation (18) and (19), 4 soil moisture holding capacities have been selected to represent various soil textural classes. For example, soils characterized as sandy loam were assigned a maximum available water capacity of 100 mm; very fine sandy loam and loam 150 mm; silt loam and clay loam 200 mm; and silty clay loam through heavy clay 280 mm. The moisture release curves illustrated in Fig. 3 were used in the moisture budget calculation procedure as follows:

a) curve C assumes that none of the soil water is readily available, and curve G and H assumes 30 and 50 percent is readily available, respecticely.

b) for all 4 moisture capacities "bare soil" evaporation is characterized by curve C.

c) plant transpiration from soils with 100 and 150 mm capacities is characterized by curve H, while transpiration from 200 and 280 mm soils is described by curve G.

Fig. 3



Relationships between AE:PE and available soil moisture
(From Baier & Robertson, 1966)
(Fig. 2, Baier et al., 1979)

LRRI

Also the crop rooting depth was considered to be infinite in this study with the absolute moisture content being the sole limiting factor in dictating crop water availability. To air in distinguishing between plant and soil evaporation the soil continuum was broken into two zones: a "surface" layer or zone and a subsurface layer referred to as the "plant zone". The surface zone was assumed to contain 25 percent of the total soil moisture holding capacity and both bare soil and plant transpiration were allowed to draw moisture from this zone. The plant zone was assumed to contain the remaining soil moisture and only plant transpiration was allowed to extract water from this zone.

To simulate plant development effects on the crops ability to draw moisture from the deeper plant zone it is assumed that plant transpiration occurs only from the "surface zone" until the LAI reaches a value of one (LAI=1). At this point the crop canopy has developed to the extent that it approaches total cover of the soil surface and at the same time root development has expanded to the depth where it can tap the moisture reserves in the subsurface "plant zone".

Ordering of various events has been assumed in the calculations. Plant transpiration takes place before bare soil evaporation; runoff occurs when water input to the surface through precipitation exceeds the total soil moisture holding capacity; and precipitation and runoff are assumed to occur at the end of the day.

The water budgeting begins on the date when PE first exceeds precipitation (P), herein, referred to as the Moisture Growing Season Start (MGSS). Calculation of this date was accomplished in the following manner. First, monthly values of PE were derived utilizing eq. (2). In all cases the monthly normals as previously mentioned are assumed to be notmally distributed on both a weekly and daily basis. From these data daily values of PE and P were generated using the Brooks (1943) sine curve interpolation procedure. Plotting the daily values of P and PE the date that PE first equalled or exceeded P was obtained from the intersection of the two daily curves.

A different method was used to determine the MGSS in the case where the soil remained frozen after the data PE exceeded P. From work on winter hardiness of alfalfa at various locations throughout Canada (Ouellet - personal communication) data on the last date of complete snow cover removal was obtained. Assuming that surface moisture loss through bare soil evaporation is negligible until the soil surface completely thaws, it follows that the surface remains frozen until the snow cover has been completely removed. Comparison of Ouellet's data with the date the mean air temperature first exceeded $\underline{0}^{o}C$ showed that complete snow cover removal occurred approximately 9 days later. It was assumed that the soil surface has thawed at this point and that evaporation occurred normally. Therefore, in the case when the date PE first exceeds P occurs before the date the mean air temperature (T_{mo}) exceeds $0^{o}C$ the moisture growing season start was set equal to the date $T_m = 0^{o}C$ plus 9 days (i.e., if $PE \geq P$ and $T_m \leq 0^{o}C$ then $MGSS = T_{mo} + 9$).

The total soil moisture in storage at the moisture growing season start (S_{MGSS}), was computed using the annual ratio of precipitation to PE, (P/PE). If P/PE$\geq$1, S_{MGSS} was set at the assigned field capacity (S_{FC}) (i.e. 100, 150, 200, 280 mm). When P/PE< 1.00, S_{MGSS} was reduced to (S_{FC} x P/PE).

The available soil moisture was not assumed to be reduced equally in both the surface and plant zones. Instead, since soil moisture recharge occurs in the surface zone first, eventually working down to the deeper soil layers, this manner of recharge was simulated by assuming that the total reduction in available soil moisture was reflected exclusively in the plant zone. The surface zone was assumed to be at field capacity. Therefore, at S_{MGSS} the total available moisture in storage was computed as:

$$S_{MGSS} = S_{FC} \times .25 + .75 \times SF_c - (SF_c \times (1\text{-}AE/PE)) = S_s + S_p, \qquad (25)$$

where: S_s is available soil moisture in the surface or soil zone,
and S_p is the available soil moisture in the plant zone.

<u>Evaluation of LAI</u>

Crop development was simulated over the growing season by the Leaf Area Index (LAI). Daily LAI values for each crop were derived from the expressions:

$$LAI = 2.77E\text{-}05 \times GSL^{3.113}, \qquad (26a)$$

for the first 42 days of the growing season, and thereafter as:

$$LAI = 6.691\text{-}0.9106\ GSL + .0398\ GSL^2 - 6.529E\text{-}04\ GSL^3 + 4.693E\text{-}06\ GSL^4 - 1.257E\text{-}08\ GLS^5, \qquad (26b)$$

for the remaining portion of the crops life cycle. Equation (26a, 26b) were developed by fitting polynomial expressions to the average curves depicting LAI vs time for spring wheat (Watson, 1971) and potato (Thorns, 1971).

The general relationship depicted by eq. (26) was assumed to be similar for all crops considered in this study since they represent a crop file cycle of approximately 130 days including 10 days from planting to emergency. For example, the life cycle of all crops considered varies from 108 days for wheat to a maximum of 140 days for potato; the remaining crops all reach maturity approximately 120 days after seeding. In this manner the shape of the curve depicted by eq. (26a) is virtually identical for all crops.

When $0 \leq LAI < 2.8$, this parameter plays a significant role in splitting total evapotranspiration between bare soil evaporation and plant transpiration; when $LAI \geq 2.8$, however, all of the moisture loss at the surface is accounted for by transpiration. Consequently, errors in estimating LAI by equation (26), and the subsequent effects of these on the ratio of growing season AE/PE, are minimal allowing one expression of LAI to represent all crops.

Evaluation of Workability Parameter

The agroclimatic constraint, workability, was derived from estimates of fall workday probabilities obtained from a model developed by Baier et al. (1979). The workday concept is related to workability in that it defines the risk associated with having only a minimum number of days to complete the harvest before the onset of inclement weather. The risk factor is related to the length of the growing season by the assumption that the greater the growing season in relation to the crop growing season requirements the more time is available for crop harvesting (conversely there is less risk of not completing the harvest). This relationship is simulated using a probability description for the harvest period in the form

$$W_L = 1 - \sum_{i=GSE}^{N} WD_i/(N-i), \qquad (27)$$

where: W is the workability yield loss,
L is a subscript denoting the probability level selected in the evaluation of W,
WD is the workday probability computed by the Dyer and Baier (1979) model, and
i and N are subscripts denoting the Julian dates of the beginning and end of the crop harvest period and (N-i) is the length of the harvest period.

Workability losses derived in equation (27) are inferred directly from the fall workday probability calculations through the assumption that these values reflect the probability that a given portion of the crop will be harvested in the time available. By this it is meant that if a farmer **requires** a certain number of workdays and the probability of getting this number of days is for example 70 percent, then on average only 70 percent of the crop is harvested over the long term.

TABLE 4

CROP WORKDAY LEVEL CRITERION USED IN EVALUATION OF

CROP LOSSES DUE TO WORKABILITY CONSTRAINTS

Crop	Average Frost Free Growing Period Requirement	Workday Probability Level (L) Relationship with Growing Season Length (GSL)	
Corn	130	If GSL $\geq$ 140 days	L = 50%
Soybean		If 120 $<$ GSL $<$ 140	L = 70%
		If GSL $<$ 120	L = 100%
Spring Wheat	110	If GSL $\geq$ 120 days	L = 50%
Potatoes		If 100 $<$ GSL $<$ 120	L = 70%
Phas. bean		If GSL $<$ 100	L = 100%

In the above relationship the required harvesting time "X out of N days" is defined as the workday probability level (L). As mentioned previously, L is related directly to the length of the growing period. The relationship between L and GSL is inverse with the value of L increasing as the growing season length decreases.

The growing season length effect on L was selected using the following criterion for each crop in this study: if the growing season length exceeded the crop average growing season requirements by 10 days or more, L was set at 5 out of 10 days (50%); if the GSL was within ±10 days, L was set at 7 out of 10 days or 70%; and if GSL was 10 days or more short of the average crop requirement L was assigned a 10 out of 10 day or 100% value. The specific criterion used in evaluating the workday probability level for each crop is shown in Table 4.

The fall workday probability estimation procedure of Baier et al. (1979) involves a soil moisture budgeting procedure that relates the near surface soil moisture to farm machine tractability or slippage. Therefore, depending on the surface soil moisture content each day is classified as a workday or non-workday. Probability estimates are derived from these values by applying a simple count and sort procedure involving several years of data.

For the purpose of this study frequency distributions of workdays expected in consecutive 10 day periods between May 1 and November 31 were generated using daily historical data for 44 meteorological stations throughout Canada. Tables were generated for each station representing the probability of having 1 through 10 workdays out of a possible 10 in increments of 10 day periods.

Combining these results with the criteria listed in Table 4 workability estimates were determined for each crop by averaging the probabilities for the 10 day periods enclosed in the harvesting period for the crop in question. The harvesting period was assumed to be 40 days in length for corn and soybens, and 20 days for spring wheat, potato and phaseolus bean. For all crops the harvesting period begins immediately following the date the crop reached maturity or the growing season end, whichever occurred first. An example of the calculation procedure for this parameter for two meteorological stations for wheat and corn is outlined in Table 5.

The derived workability figures for each station were mapped for each crop and superimposed onto the 1:5 million scale soils map of Canada. Workability values for each soil unit were then estimated by interpolation.

TABLE 5

CALCULATION PROCEDURE FOR ESTIMATING THE WORKABILITY CROP LOSSES AT HARROW, ONTARIO AND BRANDON, MANITOBA FOR SPRING WHEAT AND MAIZE

	Harrow, Ontario			Brandon, Manitoba			
Probability Level	50%	70%	100%	50%	70%	100%	
May 1 - May 11	93	76	36	95	87	60	
May 12 - May 21	91	87	47	97	93	67	
" 22 - " 31	98	96	51	96	93	59	
June 1 - June 10	100	96	51	95	85	48	
" 11 - " 20	100	98	49	99	92	57	
" 21 - " 30	100	93	47	96	89	47	
July 1 - July 10	100	96	58	95	91	49	
" 11 - " 20	96	91	51	100	92	60	
" 21 - " 30	98	93	58	99	93	69	
" 31 - Aug 9	98	89	49	97	93	61	Workday
Aug 10 - Aug 19	98	93	67	96	93	61	probabilities
" 20 - " 29	96 wheat	91	49	99	93	49	
" 30 - Sept 8	98	93	58	91	85	60	
Sept 9 - Sept 18	96	89	58	96	88	67	
" 19 - " 28	96 corn	84	42	96	84	63 corn	
" 29 - Oct 8	91	76	56	96	85	65	
Oct 9 - Oct 18	84	73	56	97	89	73	
" 19 - " 28	82	69	36	97	92	75	
" 29 - Nov 7	51	38	29	96	93	67	
Nov 8 - Nov 17	49	29	16	96	93	53	
" 18 - " 27	42	18	4	96	96	51	

	Harrow, Ontario	Brandon, Manitoba
Wheat	GSL = 177 days Planting date is May 1 Mature date is Aug. 19 Harvest Period Aug. 20 to Sept. 8 (20 days) GSL is 177 days ∴ L is 50% ∴ WP =(96+98)/2=97	GSL = 110 days May 25 to Sept. 11 Plant date May 25 Mature date Sept. 11 GSL $\geq$ 110 days ∴ L = 50% Harvest period Sept. 12 to Sept. 28 WP = (96+96)/2=96
Corn	Plant May 1 Mature Sept. 9 Harvest Sept. 10 = Oct. 18 GSL > 140 days L = 50% WP = (96+96+91+84)/4=92	Plant May 25 Mature Sept. 11 GSL < 130 days ∴ L = 100% WP = (67+63+65+73)/4=67

Sample Calculation:

The following example outlines the manner in which the above procedures are used to calculate potential and anticipated net biomass and dry matter yields for a corn crop for soil unit G17.

1. Location: 42^{o}N. Lat., 82^{o} W. Long. - Southern Ontario
   Altitude: 175 m

2. Growing Season Climate Information

   Growing period: 159 days
   Start of growing season: May 13
   End of growing season: October 18

Average mean 24 hour air temperature: $17.3^{o}C$

Average maximum air temperature $22.9^{o}C$

Average minimum air temperature $11.8^{o}C$

Average mean daytime temperature $20.9^{o}C$

Average incoming global solar radiation: 426.4 cal/cm^{-2} day^{-1}

3. Crop Information for Corn

   Days to maturity: 120 days
   Leaf area index (LAI) at the time of maximum growing rate: 4.0 (from Table 2)
   Harvest index: 0.35 (from Table 2)

4. Calculation of Rate of Potential Gross Biomass Production (b_{GM})

P_m - Maximum photosynthetic rate at $20.9^{o}C$: 53.97 kg $ha^{-1}hr$ (from equation 8b)

Y - Percentage difference in P_m relative to P_m = 20 kg $ha^{-1}hr^{-1}$: 169 percent (from equation 7)

PAR_c - Average amount of photosynthetically active radiation on clear days over the growing period: 355.8 cal cm^{-2} day^{-1} (from Table 1)

F - fraction of the daytime when the sky is overcast: 0.50 (from equation 5)

b_c - average rate of gross biomass production for perfectly clear days at P_m = 20 kg $ha^{-1}hr^{-1}$ over the growing season: 447.5 kg ha^{-1} day^{-1} (from Table 1).

b_o - average rate of gross biomass production for perfectly clear days at P_m = 20 kg $ha^{-1}hr^{-1}$ over the growing season: 232.7 kg ha^{-1} day^{-1} (from Table 1).

$b_{gm_{20}}$ - rate of gross biomass production at P_m = 20 kg $ha^{-1}h^{-1}$ at LAI=5: 339 kg $ha^{-1}day^{-1}$ (from equation 4)

b_{gm} - rate of gross biomass production at P_m = 53.97 kg $ha^{-1}h^{-1}$ at LAI=5: 568.0 kg $ha^{-1}day^{-1}$ (from equation 4 and 6a)

MCGR - maximum crop growth rate at LAI=4.0: 0.936 (from equation 10)

5. Calculation of Total Potential Net Biomass Production (BN_{ACT}) and Yield (BY_{ACT})

CT - maintenance respiration coefficient at 30°C: 0.0108 (for non-legume crop).

C_T - maintenance respiration coefficient at 17.3C: 0.00477 (from equation 3)

B_N - total net biomass production at LAI - 5: 21.0 t/ha (from equation 2)

MCGR - maximum crop growth rate at LAI - 40: 0.936 (from equation 10)

BN_{ACT} - actual crop potential net biomass production: 20.6 t/ha (from equation 11).

BY_{ACT} - actual crop potential dry matter yield: 7.2 t/ha (from equation 12).

6. Calculation of Moisture Stress and Workability Constraint

a) Moisture Stress Losses:

Ky - crop moisture yield response factor for corn - 1.25 (from Table 1, Doorembos and Kassam, 1979).

ETA/PE - growing season rate of actual to potential evapotranspiration - 0.894 (from equation 18)

MSF - moisture stress factor - 0.868 (from equation 16a)

b) Workability Losses:

WP - workability parameter - 0.88 (see Table 5).

7. Calculation of Anticipated Net Biomass (BN_{ANT})

Dry Matter Yields (BY_{ANT})

B_{ANT} - 15.8 t/ha (from equation 13)

BY_{ANT} - 5.5 t/ha (from equation 14)

The above example outlines the procedures used to quantify the constraint gree potential and actual anticipated yield for a corn crop during the growing season from generalized crop photosynthetic and respiration responses to average climatic factors involving radiation, temperature and precipitation. It must be emphasized that the techniques are not intended for real time prediction of actual crop production. They are intended only for evaluating the long-term crop production capability on a continental basis from a climatic point of view assuming optimum soil conditions. Actual production values can fluctuate significantly from year to year depending on the particular crop cultivar, the actual soil and climate conditions during the year, and the farm practices employed. Despite this, however, it is assumed that the yield estimates provided are representative of the long-term climatic capability and as such will provide useful input into land evaluation assessments.

The above methodology was used in assessing the land suitability in Canada for the production of wheat, corn, soybens, potatoes and phaseolus beans. The manner in which it was applied as well as the results of the assessment are not presented here but are outlined in detail by Dumanski and Stewart (1981).

Finally, it should be noted that the procedures described herein, are essentially those developed by F.A.P. (1978). Where discrepancies exist, particularly in the growing season definition and the estimates of the agroclimatic constraints, deviations from or modifications to the F.A.O. methodology were undertaken only to better reflect Canadian climatic conditions and farming practices. This was done to make the best use of the existing data base to provide the most up-to-date yield production potential assessment.

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